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Optimisation of Weld Overlay Cladding Parameters using Full-Factorial Design of Experiment

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Abstract. Weld Overlay Cladding (WOC) shares the same scientific principals as conventional welding where there are multiple governing factors that control the process and outcome. The present work employs a Design of Experiment (DoE) approach to optimising process parameters for cladding a nickel superalloy onto low alloy steel with the aim to improve productivity and quality. The arc current, the clad metal heating current were identified as the key process variables for this stage of experimentation. A full-factorial 4-by-2 test was carried out to identify the optimal levels. Results showed that there is a mild positive trend between the height of individual strings of beads and both variables. However no relationship was established with the depth of penetration, nor with the height of single or double layer stacks. The optimal level of the variables was therefore chosen to be the one that has the highest productivity rate as there were no significant differences. Further experimentation has been planned and described in this paper.

Introduction

Weld Overlay Cladding (WOC) is a surfacing technique commonly applied on subsea Oil and Gas components to impart additional properties such as wear and corrosion resistance at a more superior level. WOC involves welding one or more filler metal onto the substrate metal to form multi-layered stacks on the surface [1]. The filler metal (or clad metal) is selected based on its material characteristics. WOC is employed as it is a more cost-effective and flexible solution than manufacturing parts entirely out of superalloy. WOC can be carried out using various welding processes as they share the same principals though would depend on several criteria such as location accessibility and welding position [2, 3].

WOC is a multi-physics process – electric arc generation, thermal energy transfer, fluid dynamics and so on [4, 5]. There are various input factors that affect the process and outcome. Each factor contains a number of governing variables which are all interlinked. It is therefore important to identify the output requirements and rank the importance and effect of each variable as the process cannot be optimised without compromise. Welding optimisation remains a highly technical task due to the vast number of variables that affects the outcome to some degree. Statistical and numerical approaches such as artificial neural networks and Taguchi method are widely used to establish relationships between input variables and outcome. The selection of process variables generally lies on the outcomes that are to be optimised [6].

Process Heat Input. In any welding operation, heat is required to melt and fuse the substrate and clad metal together. The amount has to be sufficient enough to carry out fusion of the metals – materials will bond poorly or even fail to do so if the heat input is lower than required. On the other hand if it is overheated, the metals will not be able to cool and solidify hence no complete weld bead can be formed. To ensure fusion between the metals, hot wire cladding tends to be used. It is a method where a current is passed through the clad metal; this causes a heating effect within the metal which would accelerate the fusion process as less heat is required from the arc to bring the material to its melting point [7]. Despite having a large array of variables, the arc current (I_a), arc voltage (V), and arc travel speed (T) are considered as the key variables in most cases. These three

are the factors that control the process heat input (H) which can be calculated per unit length with the simplified formula in Eq. 1 below [8]:

$$H = \frac{I \times V \times 60}{t \times 1000} \times \eta \quad (1)$$

The arc efficiency (η) is defined based on the welding process employed [9]. A wide range of values has been published over the years via computational simulation or experimentation [10]. It is a common practice to choose a conservative value when designing WOC procedures.

The present work utilised an energy transfer model to approximate the heat input requirement, which originated from the concept of arc efficiency calculations. With this estimation model, process parameters were then projected and set as the levels for a full factorial design of experiment with the objective to optimise WOC in terms of productivity and clad quality.

Note: Due to confidentiality agreement, no data or further detail of the research can be revealed.

Experimental Procedure

A full factorial design of experiment was carried out. Two factors were selected – arc current (I_a) and hot wire current (I_w) as critical process variables. Eight sections of low alloy Cr-Mo steel pipe with wall thickness of 30mm were acquired as the substrate and a nickel-based superalloy was used as the clad metal. A cladding sequence, as shown in Fig. 1a, was designed to aid investigation on the interactions between strings of weld beads. Three individual strings were cladded on the upper half of each pipe section; a group of single-layer clad and a group of double-layer clad were on the lower half – this is where strings were overlaid consecutively with steps of X mm between each. The response on weld bead height was then measured using Renishaw Cyclone Scanning System to assess the effect from each factor. Three 30mm wide specimens were extracted from each pipe section. A fixture was made on the bench to hold specimen in place during the scan. Measurement was repeated 3 times on each specimen as indicated in Fig. 1b.

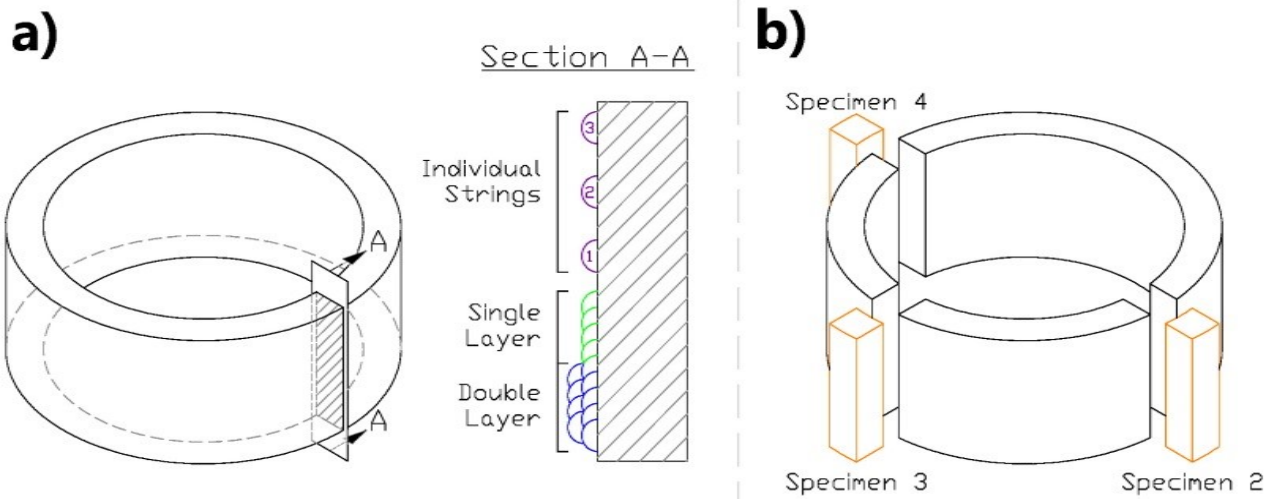


Fig. 1 a) Cladding Sequence; b) Specimen locations

Factorial design calculations. All 8 tests were designed based on an estimation model derived from arc efficiency calculations. In order to equate the amount of heat input needed for the operation, the mechanism can be broken down into three components: energy required to melt the clad metal (E_{clad}), energy required to create a weld pool on the substrate (E_{base}), and the energy transfer from the weld pool to the surrounding material ($E_{transfer}$). The effect of I_w was included in the clad metal calculation as the temperature would be raised by the current, thus less energy would be required to reach melting point. A melting efficiency (η_{melt}) was factored in as well. The sum of total energy required was then compared against the heat input from welding arc to determine the adequate values for each parameter. The calculation must satisfy Eq. 2 for fusion to take place.

$$H \geq \frac{(E_{clad} + E_{base})}{\eta_{melt}} + E_{transfer} \quad (2)$$

Level selection. A short series of preliminary tests were carried out to trail the model where the heat input parameters were selected arbitrarily and energy requirements were calculated thereafter. Model was adjusted accordingly based on the results. To set a benchmark, I_a and I_w from the existing WOC procedure were set as the first level for each factor (A1 and W1). A4 was set to reach the cladding rig's recommended duty cycle capacity. A2 and A3 were evenly spread between A1 and A4. W2 was chosen based on results from preliminary tests.

Since only choosing 2 process variables as main factors, other variables have to be balanced accordingly to have equivalent heat input to energy requirement ratio among all 8 tests. The rest of the variables – V , T , and wire feed rate (F) – were derived through iterations from the estimation model with respect to the chosen levels of I_a and I_w . Test 1 had the lowest deposition rate whereas Test 8 had the highest. As the deposition rate was predetermined, the optimal levels were defined based on clad integrity and solidification geometry of the clad. The complete 4-by-2 factorial design matrix can be seen in Table 1.

Table 1. 4-by2 full factorial matrix

Test	I_a [A]	I_w [A]	V [V]	T [mm/min]	F [mm/min]
1	A1	W1	V1	T1-1	F1-1
2	A1	W2	V1	T1-2	F1-2
3	A2	W1	V2	T2-1	F2-1
4	A2	W2	V2	T2-2	F2-2
5	A3	W1	V3	T3-1	F3-1
6	A3	W2	V3	T3-2	F3-2
7	A4	W1	V4	T4-1	F4-1
8	A4	W2	V4	T4-2	F4-2

Result and Discussion

All 8 tests showed no abnormality during the process. Visual and dye penetration examination did not show any defects either. A total of 24 specimens were extracted from the experiment pieces. The specimen profile was measured 3 times. The peak of each feature was compared among the strings, the specimens, and the tests.

Individual Strings. Measurements are presented in form of a multi-vari chart as shown in Fig. 2. It can be seen that repeatability of the measurements was poor. As the repeats were set 1mm apart, the recorded values could be reflecting irregularities on the surface caused by the arc pulsation. Height also varied among the strings and specimens. It is suspected that the solidification at different locations on the pipe section would not be the same since the availability of substrate material for heat dissipation was different - where there is more material the string height would be higher as solidification rate would be faster.

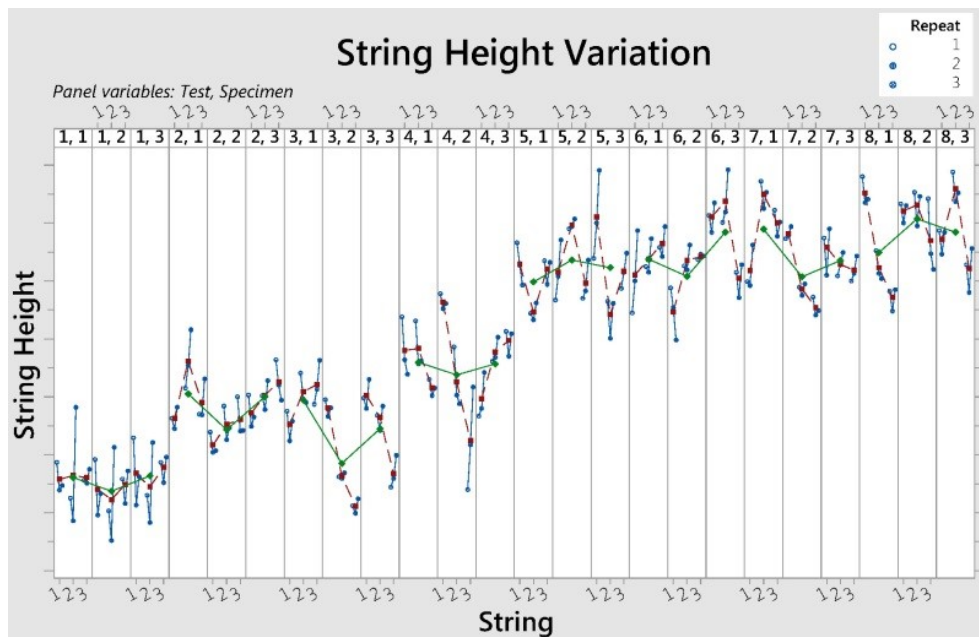


Fig. 2. Multi-vari chart of individual string bead heights

Despite height variations, there appears to be a positive trend between each test. There is a clear effect of I_a on individual string height with the most significant between A2 and A3. I_w also displayed an effect on string height with the most apparent changes being between Tests 1 and 2, and Tests 3 and 4. Even though both factors had an effect on the string height, the main effect was thought to be caused by T , the arc travel speed. As the arc travels faster, heat dwells for a shorter time around the weld pool hence quicker solidification can be observed through the string height.

Single and Double Layer Clad. Even though the individual string height of Test 1 to 8 varied, the single layer clad heights were almost constant (See Fig. 3). The positive trend seen in the individual strings is not apparent when they were laid consecutively in regular steps. The double layer clad exhibits a different pattern in height in comparison with single layer clad. This is likely to be caused by the location of where the second layer of clad was overlaid in relations to the first. There is a possibility that some strings of clad were overlaid onto one of the troughs on the first layer hence resulted in a shorter second layer.

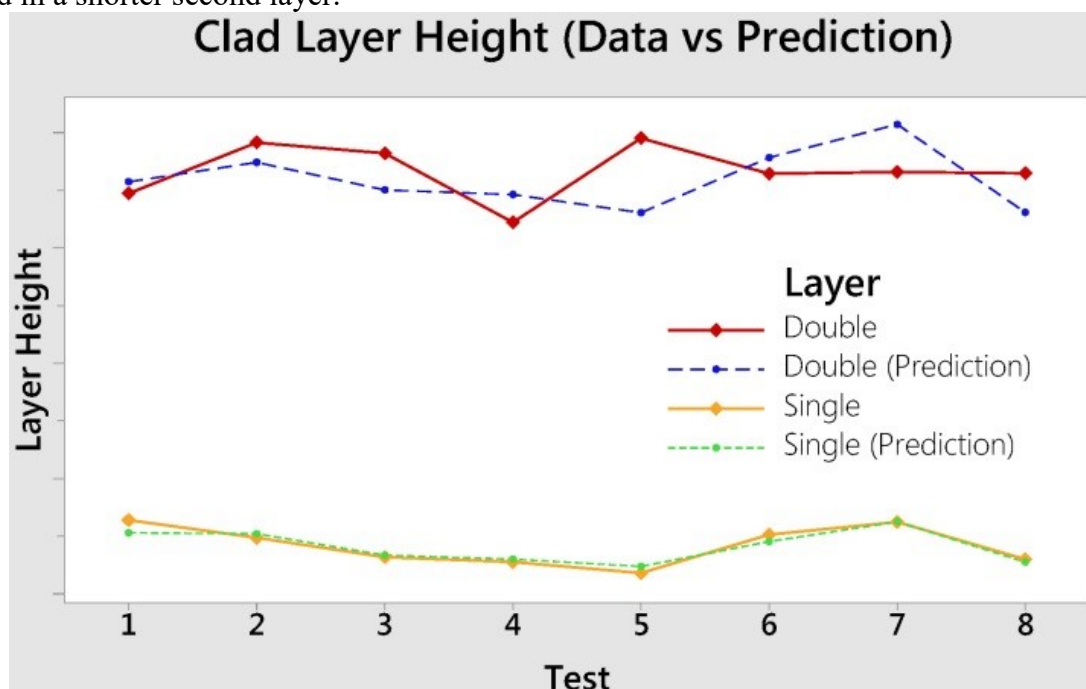


Fig. 3. Clad layer height comparison

In order to regulate the height of double layer clad, a cumulative technique using data from individual strings can be applied to predict the layered clad height for different step increments. To test the model, the predicted values were then compared against experimental data for steps of Xmm. As shown in Fig. 3, the prediction for single layer clad was consistent with data collected from the specimens. This demonstrates that the cumulative model is adequate in predicting the height of the first layer however it was problematic to estimate double layer clad height due to the overlaying locations.

Conclusion and Future Work

A full factorial 4-by-2 design of experiment was carried out with the aim to optimise weld overlay cladding process. Arc current, I_a , and hot wire current, I_w , were chosen as critical process variables of WOC and the levels were chosen by using a calculation model. The values of relevant WOC variables were derived from the model with regards to the chosen experiment levels. Results were analysed in terms of the height of each clad feature – individual strings, single layer, and double layer. It was discovered that both I_a and I_w had an effect on the individual strings – both produced a positive trend towards the height. Despite so, the arc travel speed was thought to have contributed to the effect as the heat from arc dwelled for a shorter period of time when the speed increased. In spite of the effect seen in the individual strings, no apparent change was observed in the single layer or double layer clad. The single layer clad appeared to be consistent throughout but the double layer was not. This is suspected to be caused by the different locations of where the second layer of clad was overlaid. Test 8 therefore contains the optimal levels for I_a and I_w as it has the highest deposition rate.

The present work exhibited that WOC parameters can be designed based on calculations to achieve desired height of a clad layer and altering I_a and I_w did not appear to affect such. It has been demonstrated that productivity can be improved by adjusting the parameters whilst balancing the heat input. It has also been displayed that the height for a given overlaying step size can be estimated using cumulative calculations with empirical data from individual strings.

Further experimental data will be collected to build a more reliable model to predict clad height for any given step size or number of layers. This can potentially improve the production efficiency as the amount of clad can be tailored to each part so that no extra material is wasted or additional time is spent on the extra material. Moreover, future factorial experiments will be carried out with slightly different heat input to Test 8. All parameters will be derived from the calculation model to balance the selected heat inputs. These further tests will be able to confirm whether there are other optimal levels that lie beyond those of Test 8.

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